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The change from accretion via a thin disk to a coronal flow: dependence on the viscosity of the hot gas

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Abstract. We study the transition from the geometrically thin disk to the hot coronal flow for accretion onto black holes. The efficiency of evaporation determines the truncation of the geometrically thin disk as a function of the black hole mass and the mass flow rate in the outer disk. The physics of the evaporation was already described in detail in earlier work (Meyer et al. 2000b). We show now that the value of the viscosity parameter for the coronal gas has a strong influence on the evaporation efficiency. For smaller values of the viscosity evaporation is less efficient. For a given mass flow rate from outside the geometrically thin disk then extends farther inward. Spectral transitions between soft and hard states are then expected for different mass flow rates in the outer disk. The physics is the same for the cases of stellar and supermassive black holes systems.

Key words. accretion disks – black hole physics – galaxies: nuclei – X-rays: galaxies

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1. Introduction

For accretion onto black holes at low, sub-Eddington accretion rates the commonly accepted standard picture is that at larger distance the mass accretes via a cool geometrically thin, optically thick disk and changes at a certain distance to a hot coronal vertically more extended gas flow. Accretion in this inner region occurs in a different mode (advection-dominated accretion flow, ADAF) where advection rather than radiation removes the locally generated accretion heat (for reviews see Narayan et al. 1998, Kato et al. 1998). The physics is the same for accretion onto stellar black holes and the black holes in AGN. This picture of a cool geometrically thin disk (with a corona above its inner part), usually modeled using an alpha-viscosity parameterization, together with the ADAF inside was supported by the spectral fits based on this model. In the work of Esin et al. (1997) such a situation was considered and the spectral transitions observed for Nova Muscae 1991 were successfully described by a series of model disks taking the transition to the ADAF at different distances from the black hole. Arising from the difficulty to fit also radio and submillimeter observations it was suggested that the bulk of accreting mass and energy could be carried off by a wind (Blandford & Begelmann 1999). Apart from the question whether wind loss is present or not it is important where and in which way the accretion flow changes to the mode of an advection-dominated flow.

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Evaporation of mass from the thin cool disk at the midplane to a hot coronal layer above offers a concept to understand the transition. Such a corona exists predominantly above the inner region of the cool disk. The computation of the vertical structure of the corona allows to determine the amount of mass which flows inward in the corona for each distance from the black hole or compact star, depending on its mass (Meyer & Meyer-Hofmeister 1994). A detailed description of this process with application to disks around black holes is given in Meyer et al. (2000b). With decreasing distance from the black hole more and more mass flows in the corona. Where the coronal flow reaches 100% of the total accretion flow the cool disk in the midplane ends and inside is only a hot coronal/advection-dominated flow. We consider the coexistence of thin disk and corona for distances of a few hundred to a few thousands of Schwarzschild radii, which applies to the situation around stellar black holes or nuclei of low-luminosity galaxies. These are the sources for which the spectra were successfully fitted using the ADAF model (Narayan et al. 1998).

The evaporation efficiency depends strongly on the viscosity of the hot coronal gas as already indicated by an analytical approximation formula (Meyer et al. 2000b). Original computations were carried out for a standard value $\alpha = 0.3$. In the literature various α-values were discussed. The aim of the present paper is to compute the evaporation efficiency for different viscosity values in de-

tail and to evaluate the consequences for the location of the transition.

In Sect. 2 we give a short description of the physics of evaporation and of our modelling. In Sect. 3 we summarize the viscosity parameters in the literature. In Sect. 4 we present our results. In Sect. 5 we summarize our results and discuss which other effects might also influence the transition.

2. The physics of evaporation

The amount of gas which flows in the corona is the amount evaporated from the cool disk minus wind loss. The equilibrium established between the hot gas and the cool disk determines this amount. The coronal evaporation flow physically results from the following mechanism. The hot corona above the cool disk atmosphere transports heat downward by electron conduction. In the lower layers the temperature decreases from its high coronal value to a low chromospheric value, heat conduction becomes ineffective, and the thermal heat flow has to be radiated away. The efficiency of radiation (in the optically thin case) depends on the square of the particle number density while the heating is proportional to the density directly. If this density is too small to radiate sufficiently, the material will heat up and increase the density in the corona. In this way a corona of a given temperature (or a given heating rate) will "dig" itself so deep into the chromospheric layers that a density is reached which is able to radiate away downward heat conduction, and a stationary state is obtained. This also establishes the final density in the corona by way of pressure equilibrium between chromosphere and corona. The gas in the corona still has angular momentum and thereby behaves much like an (albeit thick) accretion disk: Friction transports angular momentum outward and matter flows inward towards the central object. In the steady state it is replaced by matter evaporating from the cool disk.

This equilibrium is found computing the vertical structure of the corona taking into account the relevant processes. We simplify the physical two-dimensional situation, for which an exact description is complicated, additionally difficult due to sonic transition at the free upper boundary. We describe the evaporation process by introducing a simplifying one-zone model for the interaction of corona and disk. This leads to a set of four ordinary differential equations for the variables temperature, pressure, mass flow and heat flux (Meyer et al. 2000b) as a model for the equilibrium between cool disk and corona near the inner edge of the thin disk. Boundary conditions are (1) at the bottom, $z = z_o$, no heat inflow and a chromospheric temperature, (2) at the upper boundary no inflow of heat from infinity and no pressure at infinity (this requires sound transition at a certain height z_1). A detailed derivation of the formulae and a description of the technique of finding the adequate solutions is given in Meyer et al. (2000b).

The evaporation efficiency strongly depends on the mass of the compact central object. For a given mass the efficiency increases with decreasing distance to the center (except in an innermost part). Earlier the coexistence of a cool disk and a corona had already been applied to disks in dwarf nova systems (Meyer & Meyer-Hofmeister 1994, Liu et al. 1995). The situation is the same in disks around neutron stars, stellar and supermassive black holes. The quantities accretion rate and distance can be written in units of Eddington accretion rate and Schwarzschild radius ($\dot{M}_{\rm Edd} = 40\pi GM/\kappa c$, $r_{\rm S} = 2GM/c^2$, with M mass of central black hole and κ electron scattering opacity). For the properties of two-temperature, optically thin ADAFs (Narayan et al. 1998) such an invariant description was used and the results were successfully applied for accretion on stellar black holes and galactic nuclei. Our relation between evaporation rate and distance also becomes invariant with the above normalization. The transition to a coronal flow around massive black holes in galactic nuclei was discussed in Liu & Meyer-Hofmeister (2001).

The compatibility of our modeling of the transition with the ADAF concept is discussed in Liu et al. (1999). We can expect a smooth transition from an thin outer disk + corona to an ADAF.

Różańska & Czerny (2000a, 2000b) also investigated the coexistence of the hot and the cold gas around galactic black holes and in AGN. Their work follows in principle the same line as the work of Meyer & Meyer-Hofmeister (1994) and Meyer et al. (2000b) on the equilibrium between corona and thin cool disk around a white dwarf or a black hole, but focuses on the innermost regions near the black hole. Though the physical picture is basically the same the results differ surprisingly in detail: The accretion rate is higher, e.g. at log $r/r_{\rm S} = 4$ and for $\alpha = 0.1$ their rate is higher by a factor $\geq$10 than ours. The maximal coronal mass flow rate is reached at smaller distance from the black hole. Różańska & Czerny (2000a, hereafter RC2000) take a difference between electron and ion temperature into account and include Compton cooling by soft photons from the underlying disk. Both effects were neglected in our treatment because they were unimportant for the coronal structure at distances down to that of the maximal evaporation rate. This is confirmed by recent computations (Liu et al. 2001) including these effects.

Thus the difference between the results must be caused by other differences in the approximations. Mainly two facts may be important in this respect. The semi-analytical approach considers the corona as one layer of constant pressure and thickness $z = r$. The computed vertical structure of the corona in Meyer (2000b, Fig.2) has a much narrower pressure scaleheight, at height $z = r$ the pressure has dropped already by a factor of 20. This means much less friction and therefore less heating. A further possible significant difference appears in the treatment of the energy carried by friction. RC2000 take the fraction of viscous heating that is caused by advection as proportional to the ratio of ion temperature to virial temperature with a factor 1. In our treatment solving the radial diffusion equation this factor comes out about 5 times larger. The two differences appear to lead to a sig-

nificantly cooler corona in our work and may therefore well account for the difference in the results. In Fig. 4 of Meyer et al. (2000b) we show a detailed evaluation of the local energy balance at the distance of maximal evaporation efficiency. One sees that gains and losses of energy vary significantly between the bottom of the corona and vertical height $z = r$. It is therefore difficult to evaluate the changes arising from the approach of RC2000 using only one layer of constant pressure and thickness $z = r$. (Note in this context that there is no difference in the physical treatment of the lower boundary condition. We include the full equilibrium between transport of matter and conductive energy and radiative losses in our equations. For the lowest region near the interface between corona and disk chromosphere (energetically of very little importance) this reduces to the profile that was already derived by Shmeleva & Syrovatskii (1973) for the case of the solar corona.) Considering these arguments it might be preferable to compute the vertical coronal structure.

For the innermost region Deufel & Spruit (2001) investigated the properties of an accretion disk illuminated by ions from the hot corona.

3. Values of the hot gas viscosity

In the literature different values for the α-parameter are discussed. For the ADAF model fits of the spectra of stellar black holes $\alpha = 0.1$, but also $\alpha = 0.3$ were used (Narayan et al. 1996, Narayan et al. 1997, Esin et al. 1998). For the modeling of the spectral state transitions of Nova Muscae the value α =0.25 seemed to give the best fit (Esin et al. 1997). Later the value 0.1 was used for modeling the spectra of truncated thin disks in low-luminosity AGN (Quataert et al. 1999). Reasons for the choice of the α parameter are discussed in Quataert & Narayan (1999). Again $\alpha = 0.3$ was used for low-radiative-efficiency accretion in the nuclei of elliptical galaxies (Di Matteo et al. 2000). Różańska & Czerny (2000a) used the value 0.1 for their analysis of the two-temperature corona. (The parametrization used in different investigations is not always the same, compare Sect. 5.3).

Another source of knowledge about the viscous stress are magnetohydrodynamic (MHD) simulations of the inner accretion disk. It is now becoming increasingly clear that the mechanism of angular momentum transport is turbulent magnetic stress (Balbus & Hawley 1998). In their global MHD simulation Hawley & Krolik (2001) investigated the radial structure of disks accreting under influence of MHD turbulent stresses. From their results they find that α as a function of radius is below 0.1 in the innermost part and varies between 0.1 and 0.2 further out (their Fig. 13). Note however that this is heavily weighted for the disk interior and is not characteristic for the atmosphere where gas pressure is low and the magnetic field is retively strong (Hawley et al. 2001). (To really relate this to the viscosity parameter used for our computations we would have to consider a magnetic pressure contributing to the “total” pressure to a specified degree).

In view of these different values we determined the evaporation efficiency here for values 0.1 and 0.2 in addition to the earlier results based on 0.3.

4. Computational results

We carried out computations for accretion onto a black hole of $6M_\odot$ at distances r from $10^{8.6}$ to $10^{10.5}$ cm, which corresponds to $10^{2.35}$ to $10^{4.25}$ $r_{\rm S}$, respectively, with viscosity parameters α 0.1 and 0.2. In Table 1 we list the new results for a number of distances r, together with the earlier results for the parameter 0.3. $\dot M(r)$ is the total amount of matter evaporating from the thin disk truncated at distance r. Mass flow rate $\dot M$ and distance r are also given in units of Eddington accretion rate and Schwarzschild radius. The relation between $\dot M$ and r is invariant with respect to changes of the central mass M if accretion rates and distances are measured in these units. The same is true for the coronal temperature (compare Fig. 3 and the comments in Meyer et al. 2000b). The values of pressure at the lower boundary are listed for a discussion of the effect of an outer pressure on the coronal structure.

In Fig. 1 we show the evaporation rate at different distances for the three values of the viscosity parameter $\alpha =$ 0.1, 0.2, 0.3. Note that three similar rates are considered: at the inner edge of the thin disk the evaporation rate is equal to the mass flow rate (this fact causes the truncation of the thin disk there). The mass flow rate in the corona is equal to the evaporation rate minus wind loss. The accretion rate onto the black hole is equal to the mass flow rate in the corona, if no wind loss occurs further in. The result shows two important changes: (1) The evaporation efficiency at a given distance r is much lower for a smaller viscosity, up to a factor of 10 for $\alpha = 0.1$ compared to 0.3; (2) for smaller α, the evaporation efficiency reaches its maximum at larger distances from the black hole, at about $r = 10^{9.2}$cm for $\alpha = 0.2$ and $r = 10^{9.75}$cm for 0.1 ($r = 10^{8.8}$cm for $\alpha = 0.3$). This strong dependence on the viscosity parameter is in qualitative agreement with our earlier analytical estimate (Meyer et al. 2001). The estimate however was based on a consideration of the global balance of the various energy terms and also neglected wind losses.

These quite different values for different α indicate that, for a given mass flow rate in the outer thin disk the disk truncation occurs at very different distances. While, in the case of a $6M_\odot$ black hole the mass flow of $10^{-10} M_\odot/yr$ ($10^{15.8}$g/s), leads to the disk truncation at $10^{10.26}$ cm for $\alpha = 0.3$ the thin disk would already extend inward all the way towards the last stable orbit for $\alpha = 0.1$. A disk truncation for $\alpha = 0.1$ would only be predicted for very low mass flow rates in the outer disk. a 'hole' in the thin disk would then occur in much fewer cases.

Also shown in Fig. 1 is the maximal temperature in the corona at the inner edge of the thin disk measured in units of the virial temperature $T_{\rm virial} = GM/(r \cdot \frac{\Re}{\mu})$. We see that from distances of $10^{10.3}$cm on outward the ratio

Table 1. Evaporation efficiency in a disk around a $6M_\odot$ black hole for different values of the viscosity parameter α

α	$\log r$	$\log \dot{M} = \log(2\pi r^2 \dot{m}_0)$	$\log P_0$	$\log T_{\max}$	$\log r/r_{\rm S}$	$\dot{M}/\dot{M}_{\rm Edd}$
0.1	9.6	15.22	5.10	7.91	3.35	1.99×10^{-4}
	9.8	15.31	4.60	7.83	3.55	2.45×10^{-4}
	10.0	15.22	3.91	7.69	3.75	1.99×10^{-4}
	10.2	14.95	3.16	7.51	3.95	1.07×10^{-4}
	10.5	14.52	1.98	7.24	4.25	3.97×10^{-5}
0.2	8.9	16.46	7.75	8.66	2.65	3.46×10^{-3}
	9.1	16.65	7.31	8.62	2.85	5.36×10^{-3}
	9.3	16.63	6.70	8.48	3.05	5.12×10^{-3}
	9.5	16.51	6.03	8.32	3.25	3.88×10^{-3}
	9.7	16.32	5.30	8.14	3.45	2.51×10^{-3}
	10.0	15.96	4.16	7.85	3.75	1.09×10^{-3}
	10.5	15.29	2.23	7.35	4.25	2.34×10^{-4}
0.3	8.5	16.97	9.11	9.04	2.25	1.13×10^{-2}
	8.8	17.26	8.45	8.97	2.55	2.16×10^{-2}
	9.0	17.21	7.83	8.82	2.75	1.95×10^{-2}
	9.3	17.00	6.79	8.57	3.05	1.20×10^{-2}
	9.7	16.55	5.30	8.19	3.45	4.28×10^{-3}
	10.0	16.15	4.14	7.90	3.75	1.71×10^{-3}
	10.5	15.48	2.21	7.41	4.25	3.62×10^{-4}

Notation: $\dot{M}$ evaporation rate; $\dot{m}_0$ and P_0 vertical mass flow density and pressure at the lower boundary of the corona, $T_{\max}$ temperature at the upper boundary (sound transition); quantities $r/r_{\rm S}$ and $\dot{M}/\dot{M}_{\rm Edd}$ scaled to Schwarzschild radius and Eddington accretion rate. $r, \dot{m}_0, P_0$ in cgs units, T in Kelvin.

becomes almost constant and approaches values around one tenth. This is a measure for the pressure scaleheight in the disk, smaller for smaller values α.

The fraction of mass carried away by the wind also changes with the viscosity. For $\alpha = 0.3$ the fraction increased from a very low value at the evaporation efficiency maximum (near log r=8.8) to about 20% (see fraction λ in Table 1, Meyer et al. 2000b). If we want to compare this with the new results we have to do this at comparable distances (same factor in radius, relative to the radius of the evaporation maximum). The fractions 0.22 at $10^{10.1}$cm (for $\alpha = 0.3$) and 0.17 at $10^{10.5}$cm ($\alpha = 0.2$) show that the part carried away by the wind decreases with α. This corresponds to the lower temperatures reached and the smaller pressure scaleheight.

5. Discussion

5.1. Further effects on the transition to the hot flow

The inner accretion regions considered here are in principle embedded in surrounding gas. If the embedding gas pressure would be sufficiently high so that the coronal gas pressure can be overcome the solution would be significantly affected and both heat and gas could flow into the corona from above. In Table 1 the values of the pressure at the transition from disk atmosphere to corona are listed. The pressure values relevant for the comparison might be a factor of a few smaller (for an example of coronal structure see Meyer et al. 2000b, Fig.2). Cooling flows as discussed in the literature occur at very much larger distances than discussed here and are hardly relevant in this context.

Of more direct influence however could be a magnetic field that was carried out with a wind from the innermost ADAF type accretion region and could spread out like an umbrella over the disk. If its pressure becomes comparable to the pressure of the coronal evaporation flow the latter could be suffocated and possibly interesting alterations on the evaporation transition model may result.

5.2. Consequences from the new results for the evaporation efficiency

The question arises whether observations can help to discriminate between different α values. We shortly summarize here these studies, first the ones concerning stellar black holes, then applications to AGN.

For X-ray novae containing a black hole we determined (using $\alpha = 0.3$) the truncation of the thin disk taking the mass flow rates from the ADAF based spectral fits. We found the truncation of the thin disk in good agreement with the location of the inner disk edge inferred from the observed H_α emission line (Meyer et al. 2000b). Also in good agreement was our prediction for the spectral state transitions (Meyer et al. 2000a) which happen at X-ray luminosities of about 10^{37}erg/s (Tanaka &Shibazaki 1996) for most sources. A thin disk truncation based on the new results for $\alpha = 0.1$ would not give a good description compared to observation. Also Quataert & Narayan (1999) had pointed out that large values, about 0.25, are needed in applications of the ADAF model to X-ray bina-

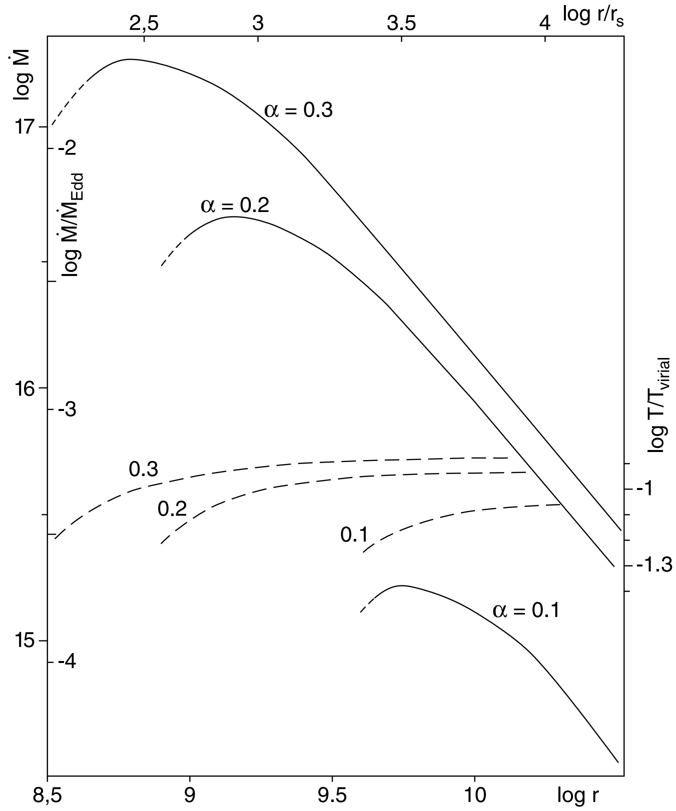

Fig. 1. Solid lines: Mass evaporation rates $\dot{M}$ from a cool disk with inner edge at distance r from the central object for various α-viscosity values. Rate of inward mass flow in the corona is $\dot{M}$ minus wind loss. (Evaporation rate and distances also given in units of Eddington accretion rate $\dot{M}_{\rm Edd}$ and of Schwarzschild radius $r_{\rm S}$). The disk is truncated at that radius where the evaporation rate equals the mass flow rate in the cool disk. The short-dashed part of the relations indicates a further decreasing evaporation efficiency (reliable results there require the consideration of a two-temperature corona). Dashes lines: coronal temperatures T at the inner edge of the thin disk measured in units of virial temperature.

ries. Further support for the choice of $\alpha = 0.3$ comes from the fact that with this evaporation rate the long outburst cycles of X-ray novae can be understood. The evaporation is an important feature for the disk evolution during quiescence with good agreement between observation and modeling concerning the amount of matter accumulated in the disk for the next outburst and the recurrence time as shown in detailed investigations for A0620-00 (Meyer-Hofmeister & Meyer 1999, 2001).

Concerning the truncation of the geometrically thin disks around black holes in galactic nuclei the situation is not so clear. For M87 and NGC 4649 the truncation determined from the evaporation efficiency computed for $\alpha = 0.3$ (Liu et al. 1999, Liu & Meyer-Hofmeister 2001) gives agreement with the truncation deduced using the ADAF based spectral fit (Narayan et al. 1999). But for low-luminosity AGN the observed UV flux seems to demand a truncation far inward for mass flow rates roughly similar in both cases (Quataert et al. 1999), which could not be explained with a smaller viscosity value in our model: For the discussed mass flow rate and a small viscosity value the disk would instead reach inward towards the last stable orbit and the spectrum would be soft. This discrepancy might point to further effects, maybe from a magnetic field, on the transition from thin disk + corona to the ADAF.

A strong dependence of the evaporation process on the chosen viscosity parameter was also found by Różańska & Czerny (2000a). They show the change of the evaporation rate for values α between 0.05 and 0.1. The changes are qualitatively similar to what we find, but differ from ours as already discussed in Sect. 2.

5.3. The viscosity parametrization

Discussing the numerical values for the viscosity parameter one should keep in mind the following aspects.

(1) The definition of the viscosity parametrization differs in different investigations. In the original formulation of Shakura & Sunyaev (1973) the viscous stress is given as $\alpha {V_{\rm s}}^2 \rho$ ($V_{\rm s}$ sound velocity, ρ density). For Keplerian rotation in the disk the viscous stress is $\frac{3}{2}\mu\Omega_{\rm K}$ which leads to $\mu=\frac{2}{3}\alpha {V_{\rm s}}^2\rho\Omega_{\rm K}$ for the dynamical and to $\nu=\frac{2}{3}\alpha {V_{\rm s}}^2\Omega_{\rm K}$ for the kinematic viscosity. Frank et al. (1992) choose $\nu=\alpha {V_{\rm s}}^2\Omega_{\rm K}$, the ansatz without the factor $\frac{2}{3}$. The latter formula is used for the computations of the ADAF in the work of Narayan et al. (1997), which means e.g. a value α=0.2 there would correspond to a value 0.3 in our investigations. To relate the results of the MHD simulations to α parameter values the Shakura-Sunyaev formulation was used in Hawley & Krolik (2001).

(2) With the acceptance of the magnetic nature of friction in accretion disks the α value should be related to the magnetic pressure. The value β, the ratio of gas pressure to magnetic pressure should account for this. The results for otherwise the same parameter α are comparable only if also this value is the same. We have not included the magnetic pressure explicitely in our analysis. Our present calculation confirms the strong influence that the value of α has on the maximal evaporation rate and the radial position of this maximum. The near quantitative agreement with the analytical estimate of this effect by Meyer et al. (2000b, equ. (57) which neglects the effects of wind loss) lends some credibility also to the estimate of the effect that an inclusion of magnetic fields in the way suggested in that paper would have. Hawley et al. (2001) have shown that hydrodynamic simulations indicate a value of $\beta > 1$ in the main body of the accretion disk that formed, but $\beta < 1$ in the atmosphere where gas pressure drops off on a much shorter scale than magnetic pressure. Taking β=0.5 as an example and reducing the effective thermal conductivity κ_0 by a mean value $\cos^2\vartheta$=0.25 for the field inclination ϑ as discussed there this would compensate nearly exactly the effect on the maximal evaporation rate of decreasing

α by a factor 3 and at the same time shift the radius of maximal evaporation even further in. Due to the strong dependencies one must be very careful when comparing different numerical values for α given in the literature.

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